CHAPTER 3

Terrestrial Ecosystem Dynamics and Responses to Change

Sentinel North

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In the context of accelerating climate change and socioeconomic development in the Arctic and Subarctic, the Sentinel North research program at Université Laval helps generate the knowledge needed to improve our understanding of the changing northern environment and its impact on humans and their health. The program fosters the convergence of expertise in the engineering, natural, social and health sciences to catalyze scientific discovery and technological innovation in support of sustainable health and development in the North.

This compendium presents a selection of results from the Sentinel North research program, from its beginning in 2017 through to the end of its first phase in 2022. The results are highlights from innovative research projects and original peer-reviewed publications, which have been integrated into five interdisciplinary chapters addressing major northern issues. Notwithstanding the scale and complexity of these issues, each chapter of the compendium aims to provide new insights through the process of integration, and fill fundamental gaps in our knowledge of the changing North.

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Introduction

Arctic and subarctic terrestrial ecosystems face significant ecological changes in response to climate shifts. Repeated aerial photograph comparisons and Normalized Difference Vegetation Index (NDVI, a proxy of primary production) analyses derived from satellite images reveal widespread yet heterogenous greening of the Arctic and subarctic (AMAP, 2021), which in turn impacts other biotic and abiotic components of the landscape. However, the consequences of these changes are diverse among species and ecosystems, leading to potential trophic interaction disruptions. In this context, it becomes necessary to increase our understanding of the effects of climate change at each level of organization, from the moleculome to the ecosystem, as well as between different ecosystems.

The harsh Arctic and subarctic environment imposes unique stresses on growing organisms such as micro-organisms, lichens, mosses and other plants. The unique biochemical adaptations they have developed to protect themselves from low temperatures, strong winds, nutrient-poor soils and high UV radiation include bioactive molecules with pharmaceutical applications (Tian et al., 2017; Carpentier et al., 2017; Bérubé et al., 2019, Séguin et al., 2023). The “moleculome”, or the ensemble of phytochemicals that a plant produces, has been described for a very small proportion of species in Canada’s north (N. Voyer, personal communication), and there is an urgent need to expand this work as climate change transforms growth and distribution patterns.

Characterized by low and slow-growing vegetation (Payette et al., 2018), the tundra biome is vulnerable to change. Lichens, in particular, are threatened by the rapid expansion of erect shrub species. Dwarf birch (*Betula glandulosa*) and other shrubs are expanding into the tundra because of factors that include warming temperatures, changes in snow dynamics, permafrost thaw, disturbances, and herbivory grazing (Mekonnen et al., 2021). This greening trend, also called shrubification, occurs at the expense of the natural flora of slow-growing lichens in the tundra (Chagnon and Boudreau, 2019) and may affect animal species which use both lichen and dwarf birch as a food source at different times of year (Béland, 2022). The growth of shrub vegetation also changes the landscape in fundamental ways, for example, by altering its reflective albedo and creating a canopy layer that changes soil temperature, permafrost depth, hydrology and micro-habitats for numerous animal species (Pelletier et al., 2018; Young et al., 2020; Domine et al., 2022).

While climate change impacts species at the individual level, it will also impact the network of trophic links relating the different species within an ecosystem. One challenge that ecologists face today is to understand how communities forming a complex interaction network will reorganize following the response of individual species to climate changes (Woodward et al., 2010). A spatial or temporal mismatch may separate previously interacting species (Schleuning et al., 2020), while novel interactions may appear due to new spatial co-occurrences (Gilman et al., 2010). In the Canadian High Arctic, for instance, several tundra vertebrates have shown little response to climate warming compared to plants and arthropods (Gauthier et al., 2013). Some species might migrate faster than others (Svenning et al., 2014), breaking the coherence of interaction networks. Trophic interactions can modify the effects of disturbances such as climate change and transfer effects to distant groups of organisms that would not have been affected otherwise (Labadie et al., 2021). Therefore, more studies integrating multiple trophic levels and temporal dynamics are needed to improve our understanding of species distribution and how they will respond to global changes (Woodward et al., 2010).

Through modelling, researchers can apply the knowledge they gain about plant and animal populations to pressing questions about the vulnerability and resilience of Arctic and subarctic ecosystems. Models can predict the overall stability of an ecosystem (Brose et al., 2019) or the effects that different climate change scenarios will have on species distributions (Bourderbala et al., 2023). Models must include seasonal variation to predict future changes (Tonkin et al., 2017), particularly in Arctic food webs where migratory species play a major role (Hutchison et al., 2020). However, as a model's complexity increases to represent the realities of real-world ecosystems, the mathematical challenges increasingly grow. Researchers from diverse disciplines, including physicians and mathematicians, have joined together with ecologists to find solutions, such as using spectral graph theory to reduce model complexity (Laurence et al., 2019) or predicting changes in complex systems using deep learning and neural networks (Laurence et al., 2020).

Whether in the greening of the Arctic tundra (Mekonnen et al., 2021) or the changing trophic network (Labadie et al., 2021), the transformation of Arctic and subarctic terrestrial ecosystems caused by climate change is visible and accelerating. The work by Sentinel North researchers described in this chapter looks at these effects from molecules to population dynamics and the broader web of interacting species. Above all, this research seeks to respond to urgent challenges of conservation and resource use by evaluating current methods to monitor biodiversity and wildlife populations (LeTourneux et al., 2022; Terrigeol et al., 2022; Bolduc et al., 2023), developing innovative tools (Bolduc et al., 2022) and working jointly with northern communities, many of which rely on traditional harvesting activities (e.g., Séguin et al., 2023; LeTourneux et al., 2021; Bates et al., 2021). Facing the challenges of climate change and biodiversity loss requires a sophisticated and integrated understanding of these terrestrial ecosystems that comes from Sentinel North's interdisciplinary approach.

KEY WORDS:
Food Webs, Shrubification, Moleculome, Modelling, Migration, Tundra, Population Dynamic

1. Northern Chemodiversity: A Distinctive Molecular Signature

Selected research highlights

The plant species that colonize Arctic and subarctic environments carry a unique yet unknown chemodiversity that could reveal molecules with medicinal properties of interest. However, this chemodiversity is threatened by climate change, which can alter the distribution of plant species and their environments.

1.1 The first ever phytochemical investigation of the volatile fraction of the dwarf birch (*Betula glandulosa*) was recently performed, revealing a molecular composition that included terpenoids, fatty acid derivatives and phenylpropanoids (Figure 1.1), as well as a volatile metabolite composition different from its *Betula* genus conspecifics. As this shrub species is an important food source for many herbivores and a structuring element of the landscape, a better knowledge of the species' molecular composition is needed to understand some aspects of its functional role in the ecosystem (Séguin et al., 2021).

Figure 1.1
Structures of the main metabolites of Betula glandulosa volatile extracts.
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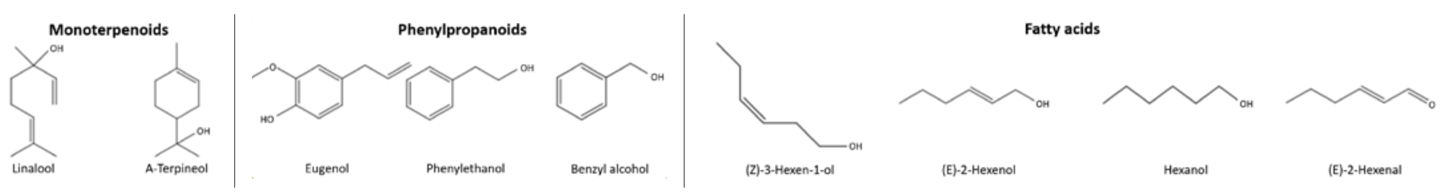
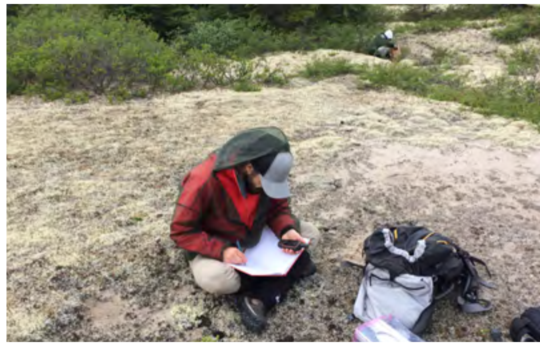


1.2 Two new dibenzofurans and 11 other lichen metabolites were isolated and identified through phytochemical studies on the lichen *Stereocaulon paschale*. Some of these metabolites showed promising antibacterial activity against the oral pathogenic bacteria *Porphyromonas gingivalis* and *Streptococcus mutans* (Carpentier et al., 2017).

1.3 The chemical synthesis of natural mortiamides from a fungus belonging to the genus *Mortierella* revealed promising activity of these molecules against the *Plasmodium falciparum* parasite, which is responsible for 50% of malaria cases. These results are particularly noteworthy because of the increased resistance of *Plasmodium sp.* to existing medications. Work is ongoing to synthesize analogues of mortiamide D with increased efficacy against *P. falciparum* (Bérubé et al., 2019).

1.4 A molecule with antiparasitic properties was isolated from essential oil extracts from dwarf Labrador tea leaf (*Rhododendron subarcticum*) in Nunavik. This molecule could be useful against parasitic infections, notably malaria (Séguin et al., 2023). Furthermore, analysis of seasonal and geographical variations in this species' moleculome will enable us to determine the best harvesting periods and sites to maximize health benefits..



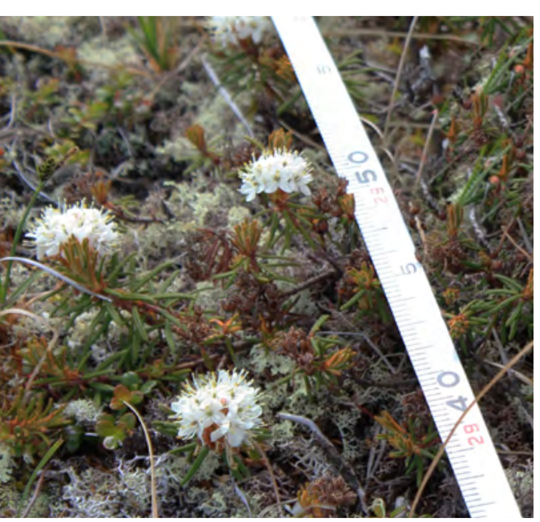
Impact of Latitude on Lichen Bacterial Diversity

A research team examined the bacterial diversity of northern lichens. This research showed that star-tipped reindeer lichen (*Cladonia stellaris*) found in northern lichen woodlands had significantly higher bacterial diversity and quantity than those found in southern lichen woodlands and that only one of these bacteria (*Methylorosula polaris*) was common to both regions. These differences in bacterial communities between the two environments remain poorly understood at present but could be related to different colonization processes or a greater presence of bacteria in northern soils (Alonso-Garcia et al., 2022).

2. Greening: Multiple Impacts in an Interconnected Environment

Selected research highlights

The expansion of shrub species, or shrubification, leads to a major restructuring of plant communities, particularly due to the presence of a shrub-formed canopy that modifies local biotic and abiotic conditions. Impacts of this transformation of the landscape occur at various levels of organization, from species to the functioning of Arctic and subarctic ecosystems.



2.1 Shrub cover has negatively impacted lichen abundance and species richness in the boreal forest-tundra ecotone. By changing the distribution of different lichen species across the landscape, shrubification could change the surface albedo, which has a significant impact on climate (Chagnon and Boudreau, 2019).

2.2 Observed and predicted changes in plant communities within the summer and winter ranges of migratory caribou (*Rangifer tarandus*) will affect this ecologically and culturally important herbivore. The decrease in lichen cover in favour of shrubs is detrimental to the cervid's dependence on this resource for winter food (Chagnon and Boudreau, 2019), but may also result in more and better-quality summer food resources, such as dwarf birch or *Carex* sp.

2.3 Camera collars used on 60 female migratory caribou showed that they foraged in wetlands during the early summer season (June and July) and in shrub areas in August. The 65,000 videos analyzed also demonstrated that the migratory caribou prefers to eat lichens, birches, willows and mushrooms. These results will help guide future management and conservation plans for this species in decline (Béland, 2022).

2.4 In the Tasiapik Valley, Nunavik, the higher vegetation cover has promoted groundwater recharge. A higher vegetation cover provides more shade and allows for trapping snow more efficiently, resulting in increased snow accumulation and a longer melting period. These results suggest that with accelerating climate change and associated permafrost thaw, vegetation growth will increase groundwater recharge in cold regions (Young et al., 2020).

2.5 The effect of shrub cover on permafrost thermal regulation is complex and varies with the season. It was shown that shrubs can cool the ground in winter by providing a thermal bridge through the snowpack. On the other hand, shrubs can warm the ground in spring when the branches absorb solar radiation and transfer heat to the ground (Figure 2.5). These results demonstrate the need to include thermal bridging processes in climate models to better predict greenhouse gas emissions associated with permafrost thaw (Domine et al., 2022).

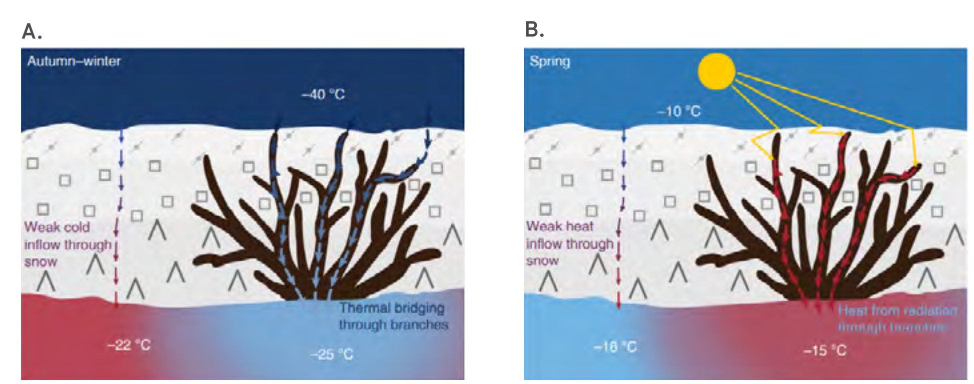


Figure 2.5
Thermal bridging through shrub branches in winter (a) and spring (b). Figure taken from Domine et al., 2022, licensed under CC BY 4.0.

> "Borealization is becoming increasingly evident. The distributions of boreal species including moose, beaver, red fox and multiple boreal bird species have all been observed to be expanding into the Arctic tundra"
>
> Speed et al., 2021

3. Changing Animal Communities

Selected research highlights

Northern ecosystems are sensitive to environmental changes, as increasing temperatures, shrub expansion and the arrival of boreal species change interactions among species. Densification and increased vertical growth of shrub species increase the amount of food and habitat available for herbivores while the arrival of boreal species modulates the interactions among existing species. Together, these changes can have unexpected impact.

3.1 A research team demonstrated that both bottom-up and top-down trophic interactions drive the functional and phylogenetic diversity patterns of vertebrate herbivores in the circumpolar Arctic (Speed et al., 2019). These results suggest that trophic interactions drive functional and phylogenetic diversity as strongly as climatic factors.

3.2 Indirect interactions within a food web may be critical to its dynamics. Although these indirect interactions are more difficult to quantify, a study demonstrated that the cascading effects of a defoliating insect in boreal ecosystems may ultimately increase the mortality rate of woodland caribou, particularly when human activities further disrupt the system (Figure 3.2). Such results are particularly crucial in the context of accelerating environmental change and anthropogenic disturbance (Labadie et al., 2021).

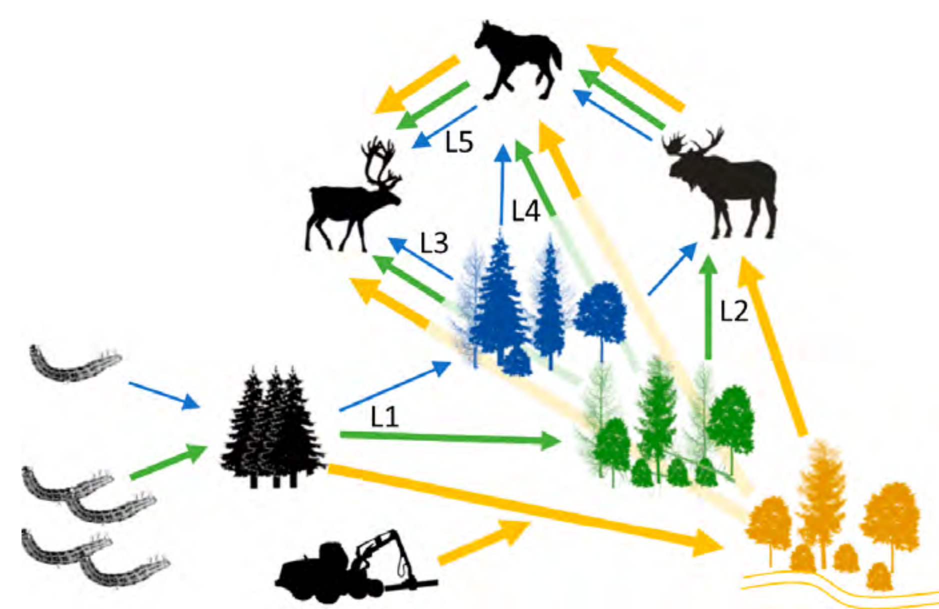


Figure 3.2
Trophic interactions illustrating the indirect effects of a defoliating insect of an early (blue arrows) and a later (green arrows) stage of an outbreak. The yellow arrows represent effects of salvage logging. Figure taken from Labadie et al., 2021, licensed under PNAS license.

4. New Technologies for Studying Lemmings: Another Step toward Understanding a Key Arctic Species

Selected research highlights

Studying Arctic animal species is often complex due to harsh climatic conditions and difficult-to-access study sites. This is especially true for lemmings, small mammals which are consumed by many different predators. Any change in their abundance and distribution can affect the entire food web they support. New technological developments are enabling us to understand the population dynamics and behaviours of these burrowing animals, particularly during the Arctic winter.

4.1 Ultra-light (1.59 g) photosensitive collars designed to record light variations while lemmings move can be used to infer the time spent in burrows. This technology shows promise for studying small mammal behaviour due to the miniaturization of the equipment (Bolduc et al., 2022).

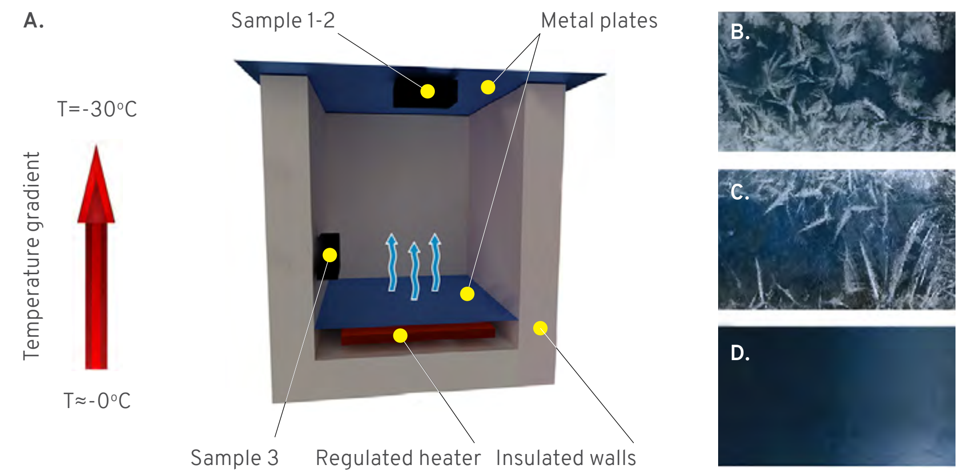
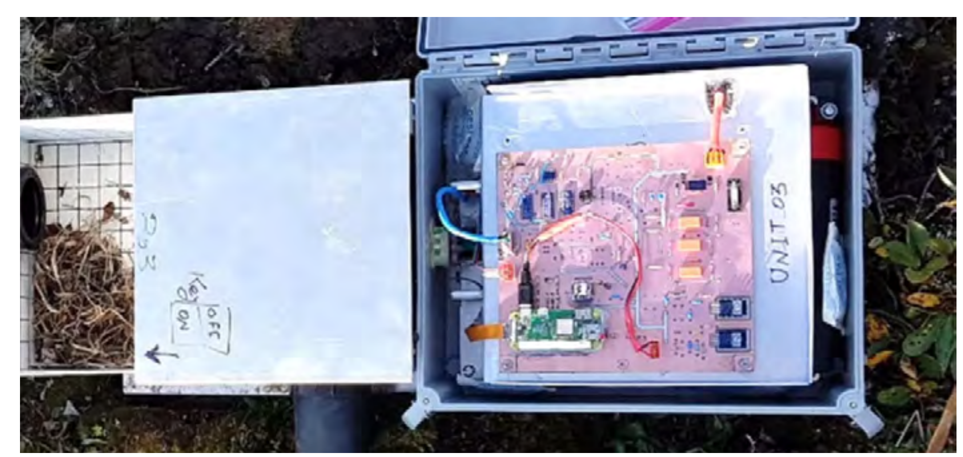


Figure 4.2
Frost formation was avoided by placing the glass sample on the lateral wall in a below freezing temperature setup. The experimental setup (a) shows frost formation on glass samples uncoated (b) and coated (c) with anti-fog solution when they are placed on top of the setup. An uncoated glass put on the lateral wall (d) shows little frost. Figure taken from Pusenkova et al., 2021, licensed under CC BY 4.0.

4.2 A research team has designed cameras capable of operating at temperatures ranging from - 20 °C to + 20 °C using a power-independent system to better understand lemming reproduction during winter. Modifications to the camera parameters have overcome problems with frost formation on the lens (Figure 4.2) and allowed for autofocus over a wide range of temperatures (Pusenkova and Galstian, 2020; Pusenkova et al., 2021).

4.3 The first complete sequence of winter lemming activity in the laboratory and then in the field on Bylot Island was conducted using an autonomous low-power camera system called ArcÇav. Among the new images obtained, the presence of young lemmings allows us to better define the timing of winter reproduction for these small mammals (Kalhor et al., 2021).



ArcÇav system

5. Predicting Ecosystem Interactions, Vulnerability and Resilience with New Modelling Approaches

Selected research highlights

The impacts of climate change are heterogeneous among species and ecosystems, with a high potential for disrupting biotic interactions, particularly by decoupling periods of high resource abundance from periods of high consumption and demand. New modelling approaches are required to better understand the effects of climate change, both on biotic interactions and ecosystem functioning.

5.1 At the regional level, both direct and indirect impacts of climate change were found on assemblage of over 100 species of birds and beetles in the boreal forest, and the magnitude of these impacts increased when their combined effect was considered. Similarly, this study suggests that the impact on the maintenance of biodiversity will be more pronounced at higher latitudes (Bouderbala et al., 2023).

5.2 A multi-seasonal model of predator-prey dynamics was developed and parameterized with empirical data collected on Bylot Island. This model can account for multiple equilibria in a simplified tundra food web. It highlighted indirect interactions not detected by a summer model, demonstrating the importance of incorporating seasonality for understanding food webs (Hutchison et al., 2020).

5.3 Food web structure can provide information about the community's ability to cope with a disturbance. However, collating the full range of relationships among a community's species is daunting. A predator-trait model was developed to overcome these difficulties, enabling us to better understand and predict differences in food web structure, community stability and ecosystem functioning (Brose et al., 2019).

5.4 Dynamical networks provide a comprehensive mathematical representation of complex systems, including ecosystems. A research team has developed a method that relies on spectral graph theory to reduce network complexity and thus predict overall system states. This approach is of both fundamental and practical interest for detecting critical transitions (Laurence et al., 2019).

5.5 A graph neural network approach, borrowed from the deep learning paradigm, has been developed to detect disturbances in a complex network, paving the way for studying complex real-world system resilience (Laurence et al., 2020).

6. Issues for Resource and Biodiversity Conservation

Selected research highlights

In light of accelerating climatic and anthropogenic pressures, it is essential to re-evaluate practices for monitoring ecosystem health and to propose new strategies.

6.1 Indicator species are commonly used to estimate local species richness. However, a research team has demonstrated that this technique is of limited value for monitoring and estimating biodiversity over large spatial dimensions. In Eastern Canada's boreal forest, for example, 57 indicator species would be needed to predict bird richness, demonstrating the need for new practices to monitor biodiversity (Terrigeol et al., 2022).

6.2 Some animal species are frequently tracked using collars. However, a long-term study found that the cumulative effect of collars and hunting pressure makes greater snow geese (*Anser caerulescens atlanticus*) more vulnerable to multiple sources of mortality (LeTourneux et al., 2022). Since 2021, these devices are no longer used for this species, posing new challenges for monitoring this overabundant population (P. Legagneux, personal communication).

6.3 The specific context of wide-scale lockdowns in the months following the global COVID-19 pandemic highlighted the fact that anthropogenic activities can have both positive and negative effects on resource and biodiversity conservation (Bates et al., 2021). During this lockdown period, hunting pressure on snow geese decreased by 54% compared to the previous year, thus positively impacting foraging efficiency and body conditions in geese (LeTourneux et al., 2021).

Research Projects Cited in this Chapter

The knowledge and technological advances referenced in this chapter were generated by several Sentinel North interdisciplinary research teams. These scientific contributions were gathered from the projects listed below, which involved, in addition to the principal investigators, numerous researchers, graduate students, postdoctoral fellows, research professionals, collaborators, partners from northern organizations and national and international partners from the public and private sectors.

- A network of automated sensors to monitor Arctic animals and environmental changes through advanced computational approaches

  Principal Investigators: Pierre Legagneux (Dept. of Biology), Audrey Durand (Dept. of Computer Science and Software Engineering)

- Comprehensive environmental monitoring and valorisation: From molecules to microorganisms

  Principal Investigator: Jacques Corbeil (Dept. of Molecular Medicine)

- Innovative optical systems to track winter life in the cryosphere

  Principal Investigator: Gilles Gauthier (Dept. of Biology)

- Interdisciplinary research to understand changing food-web dynamics and threats to food security in the northern boreal forest

  Principal Investigators: Daniel Fortin (Dept. of Biology), Jérôme Cimon-Morin (Dept. of Wood and Forest Science)

- Network analysis of umbrella and indicator species: Assessing the integrity of northern ecosystems

  Principal Investigator: Daniel Fortin (Dept. of Biology)

- The resilience of complex networks: Identifying critical indicators for efficient targeted interventions

  Principal Investigators: Patrick Desrosiers (Dept. of Physics, Physical Engineering, and Optics), Simon Hardy (Dept. of Biochemistry, Microbiology and Bio-informatics)

- Sentinel North Research Chair on the Applications and Theory of Network Analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)

- Sentinel North Research Chair on the Impact of Animal Migrations on Arctic Ecosystems

  Chairholder: Pierre Legagneux (Dept. of Biology)

Research Projects Cited in this Chapter

Some results presented in this chapter are also drawn from research projects conducted by recipients of Sentinel North Excellence scholarship and postdoctoral fellowship awards.

- Abondance et diversité des espèces lichéniques au Nunavik en contexte de changements climatiques
  Catherine Chagnon (Master's Scholarship)
- Production et caractérisation d'huiles essentielles issues de la nordicité
  Jean-Christophe Séguin (Master's Scholarship)
- Simulation de la dynamique du pergélisol en considérant l'advection de la chaleur par l'écoulement de l'eau souterraine
  Philippe Fortier (Master's Scholarship)
- Development of the smart LC shutter for the adaptive camera for subnival observation of lemmings
  Anastasiia Pusenkova (Ph.D. Scholarship)
- Influence de la prédation dans la répartition spatiotemporelle des espèces proies d'une communauté de vertébrés arctiques
  Frédéric Dulude-de Broin (Ph.D. Scholarship)
- Impact de changements récents de règlements de chasse sur la dynamique de population de la grande oie des neiges
  Frédéric LeTourneux (Ph.D. Scholarship)
- Impact des propriétés physiques de la neige sur les populations de lemmings
  Mathilde Poirier (Ph.D. Scholarship)
- Impact of wildfires on the diversity of lichen-associated viruses in a changing North
  Marta Alonso-Garcia (Postdoctoral Fellowship)
- Integrated modeling of the terrestrial water cycle in degrading permafrost environments
  Nathan Young (Postdoctoral Fellowship)

Sentinel North has developed partnerships with leading international institutions to conduct innovative and interdisciplinary research projects. The following joint collaborative projects have contributed to the results of this chapter.

- Characterization of essential oils from northern environments
  Principal Investigators: Xavier Fernandez (Institut de chimie de Nice, Université Côte d'Azur), Normand Voyer (Dept. of Chemistry)

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Ongoing Sentinel North Research Projects

Several research projects supported by Sentinel North and through joint funding initiatives are ongoing as part of the second phase of the program (2021-2025). These projects, listed hereunder, continue to fill fundamental gaps in our scientific knowledge of the changing North.

- A network of automated sensors to monitor Arctic animals and environmental changes through advanced computational approaches

  Principal Investigators: Pierre Legagneux (Dept. of Biology), Audrey Durand (Dept. of Computer Science and Software Engineering)

- Characterization of essential oils from northern environments

  Principal Investigators: Xavier Fernandez (Institut de chimie de Nice, Université Côte d'Azur), Normand Voyer (Dept. of Chemistry)
  Project jointly funded by Sentinel North and Université Côte d'Azur

- Dynamics of the Innu ancestral territory (Nitassinan) through the morpho-sedimentary and socio-cultural study of Lake Manicouagan (Reservoir)

  Principal Investigator: Patrick Lajeunesse (Dept. of Geography)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Ecogenomics of mining areas for sustainable Canadian North

  Principal Investigators: Véronic Landry (Dept. of Wood and Forest Science), Damase Khasa (Dept. of Wood and Forest Science)

- Impacts of climate change and browning on salmonid oxythermal habitat and greenhouse gas emissions in Arctic regions

  Principal Investigator: Isabelle Laurion (Eau Terre Environnement Research Centre, Institut national de recherche scientifique)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Interdisciplinary research to understand changing food-web dynamics and threats to food security in the northern boreal forest

  Principal Investigators: Daniel Fortin (Dept. of Biology), Jérôme Cimon-Morin (Dept. of Wood and Forest Science)

- Sentinel North Research Chair on the Applications and Theory of Network Analysis

  Chairholder: Antoine Allard (Dept. of Physics, Physical Engineering, and Optics)

- Sentinel North Research Chair on the Impact of Animal Migrations on Arctic Ecosystems

  Chairholder: Pierre Legagneux (Dept. of Biology)

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René Richard	15, 30
Pascale Ropars	13
Normand Voyer	5, 12, 13, 27, 30

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Open access

Open access (OA) means online and free access to research outputs.

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